Application of Implicit and Explicit Reliability Models for Incorporating Ageing Effects

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APSA Task: *Incorporating Ageing Effects*

- The PSA gives excellent opportunities for ageing safety & efficiency problems solving - Ageing PSA.
- One of the PSA tasks is an incorporation of age-dependent reliability parameters and data of certain safety-related SSCs into the PSA model and interpretation of its results.
- Task 7 of the APSA network: *"Incorporation of age-dependent reliability parameters and data of SSC into the PSA model and interpretation of its results."*

Resume

- The paper presents application of the implicit GO-FLOW & the explicit ATRD methods for incorporating ageing effects.
- Both approaches are used for preparation of comparable ageing process component and system models of the safety system - 3-train LP RHR & ECCS, and a normal operation system of a WWER-1000 (PWR) OS of MCP.
- Different descriptions of the ageing degradation for different components & by different functions growing in time – linear, 1- or 2-parametric Weibull ageing models are used.
- GO FLOW & ATRD could be used to feasibility investigation of increasing of failure, restore & repair rates of all components or reducing the surveillance intervals.

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Ageing PSAM

1. Age-critical component identification and selection
   - Ageing-screening methods to identify and prioritize the most critical age-dependent SSCs of the APSA
2. Identification and evaluation of ageing effects
   - Probabilistic models, trend/sensitivity/uncertainty analyses
   - Incorporation & integration of component-specific ageing with the plant & system level reliability analysis
3. Development of prevention and mitigation methods
   - Reliability centered maintenance
   - Reliability models for maintenance optimization

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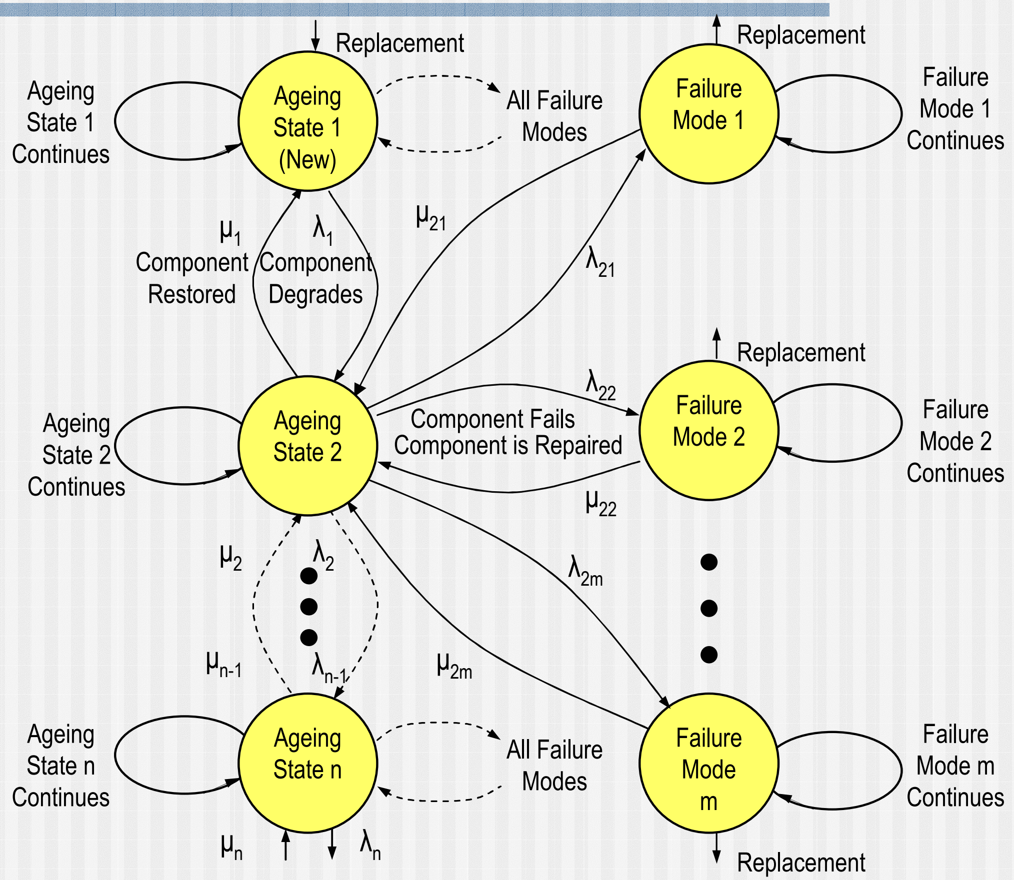
Dynamic Description of Component Ageing



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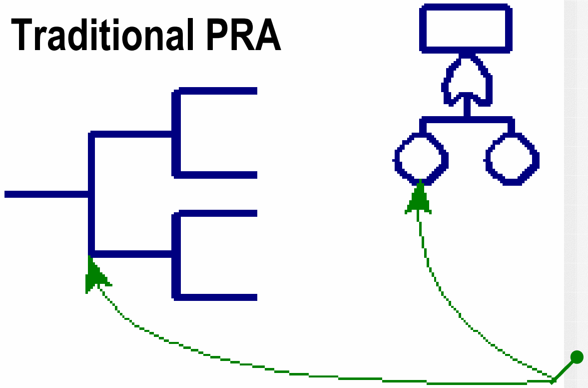
Incorporation of Age-dependence

- The **physical and dynamic** description of ageing component degradation could consist of *many ageing states*, *multiple failure modes* and *transitions between these basic events*.
- *"Plug-in" concept* is the preferable way to take into account the SSC susceptible to ageing.
- It **dynamically** embeds external *ageing physics models* directly into the PSA software and updates the component reliability database of already calculated models - *hybrid deterministic-probabilistic models*.

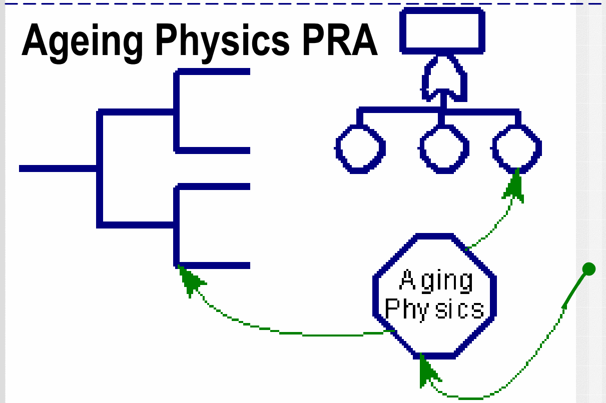
Traditional vs. Ageing Physics Model PRA

Traditional PRA



1. Obtain component failure data
2. Determine appropriate component reliability model
3. Use statistics to determine appropriate failure rate
4. Calculate component failure probabilities
5. Put probabilities in fault/event trees

Ageing Physics PRA



1. Determine applicable ageing mechanisms and affected components
2. Develop “ageing physics” models
3. Determine loading conditions on component
4. Incorporate physics model and loading conditions into PRA via fault/event trees
5. Use physics model to determine ageing-related probabilities

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ET-FT Methodology Limited Dynamics

- The conventional ET-FT methodology for reliability and risk assessment is designed to describe static relationships between logical variables and does not explicitly treat time, physical process variables, ageing or human behaviour.
- The overcoming of quasi-static tree models limitations needs essential extensions or alternative methodologies for due assessment of reliability and risk.
- The alternative methodologies should include extensions of the ET-FT approach, rather than revising the methodology itself, however, they could be intended also to supplant the ET-FT approach in certain situations.

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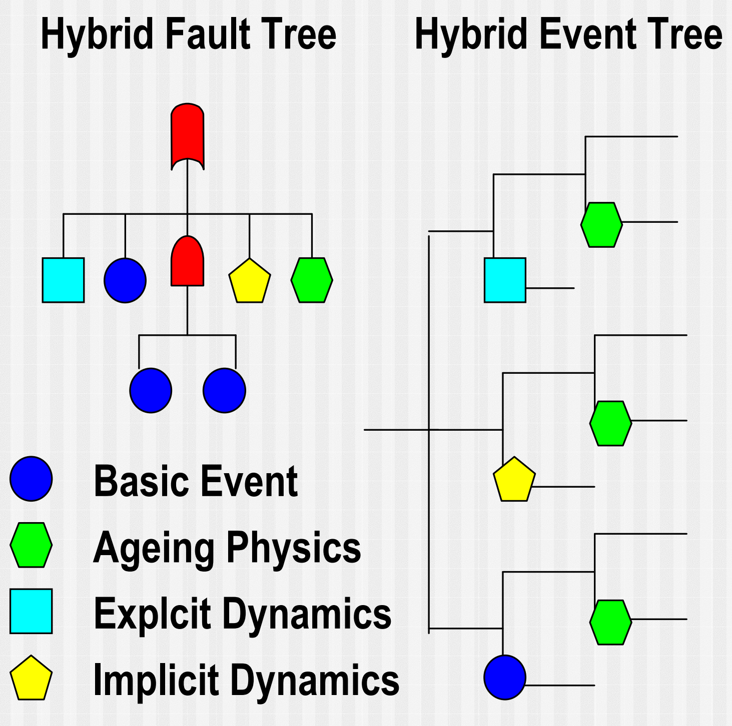
Ageing Physics, Implicit & Explicit Dynamics
Hybrid Deterministic-Probabilistic Models



1. Obtain component failure data, generic data, or combination of both
2. Determine appropriate component reliability model [e.g., 1-EXP(λT)]
3. Use statistics (e.g., Bayes) to determine appropriate failure rate
4. Calculate component failure probabilities
5. Put probabilities in fault/event trees
6. Determine applicable ageing mechanisms and affected components
7. Develop 'ageing physics', 'explicit dynamics' or 'implicit dynamics' models
8. Determine loading conditions on component
9. Incorporate hybrid models and loading conditions into PRA via FT/ET, ATRD, GO-FLOW, etc.
10. Use hybrid model to determine ageing-related probabilities

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Applicability, Spectrum & Features of Dynamic System Reliability Methods

- *ET-FT extensions* - expanded ETs, GO-FLOW, digraph-based FT construction, ATRD
- *Implicit state-transition methods* - continuous ETs (semi-Markov chains), dynamic logical analysis methodology (DYLAM), GO-FLOW, dynamic ETs (DETAM), discrete/analogue event (Monte Carlo) simulation;
- *Explicit state-transition methods* - event sequence diagrams, explicit Markov models, ATRD;
- *"Cell-to-cell" approach* - ATRD.

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GO-FLOW Methodology

- It is a success-oriented system reliability analysis methodology.
- GO-FLOW chart is constructed with standardized operators and signal lines.
- Analysis is performed by one GO-FLOW chart and one computer run.
- GO-FLOW analysis support system has been developed.
- Developed by Matsuoka & Kobayashi
(National Maritime Research Institute, Japan, in 1988)

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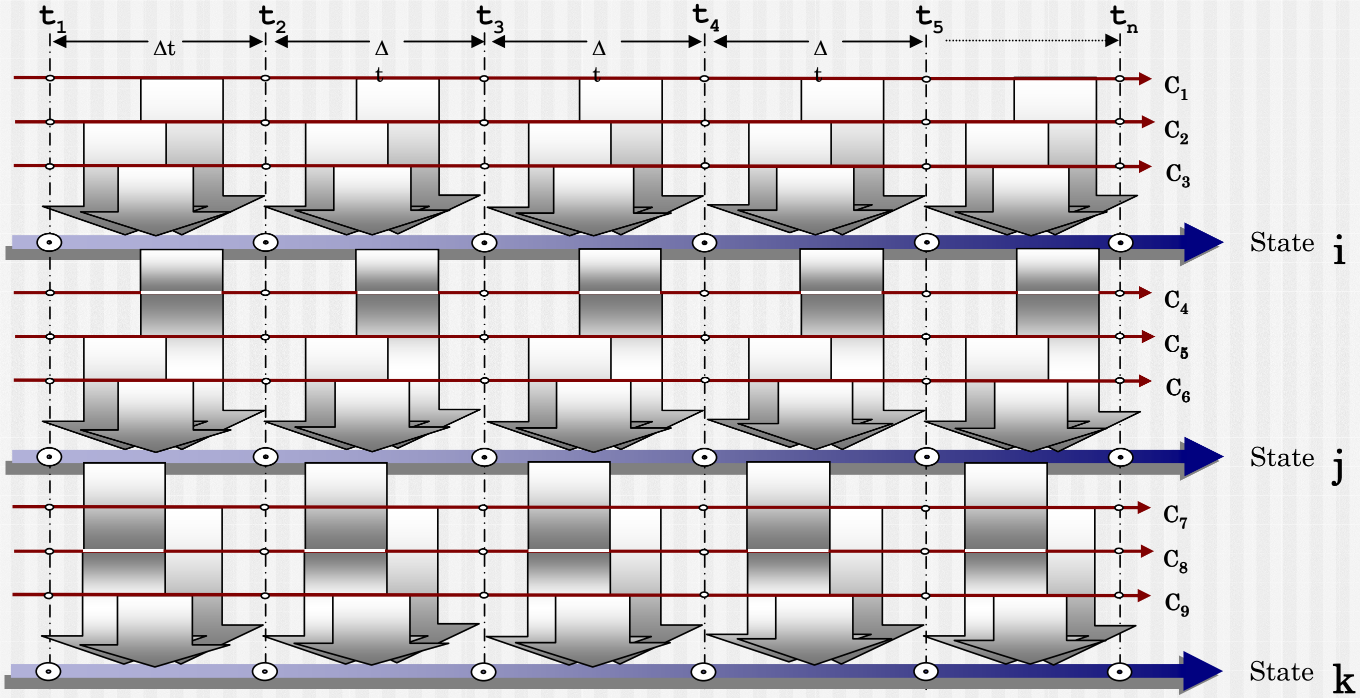
GO FLOW Procedure



Conceptual image of GO-FLOW analysis procedure

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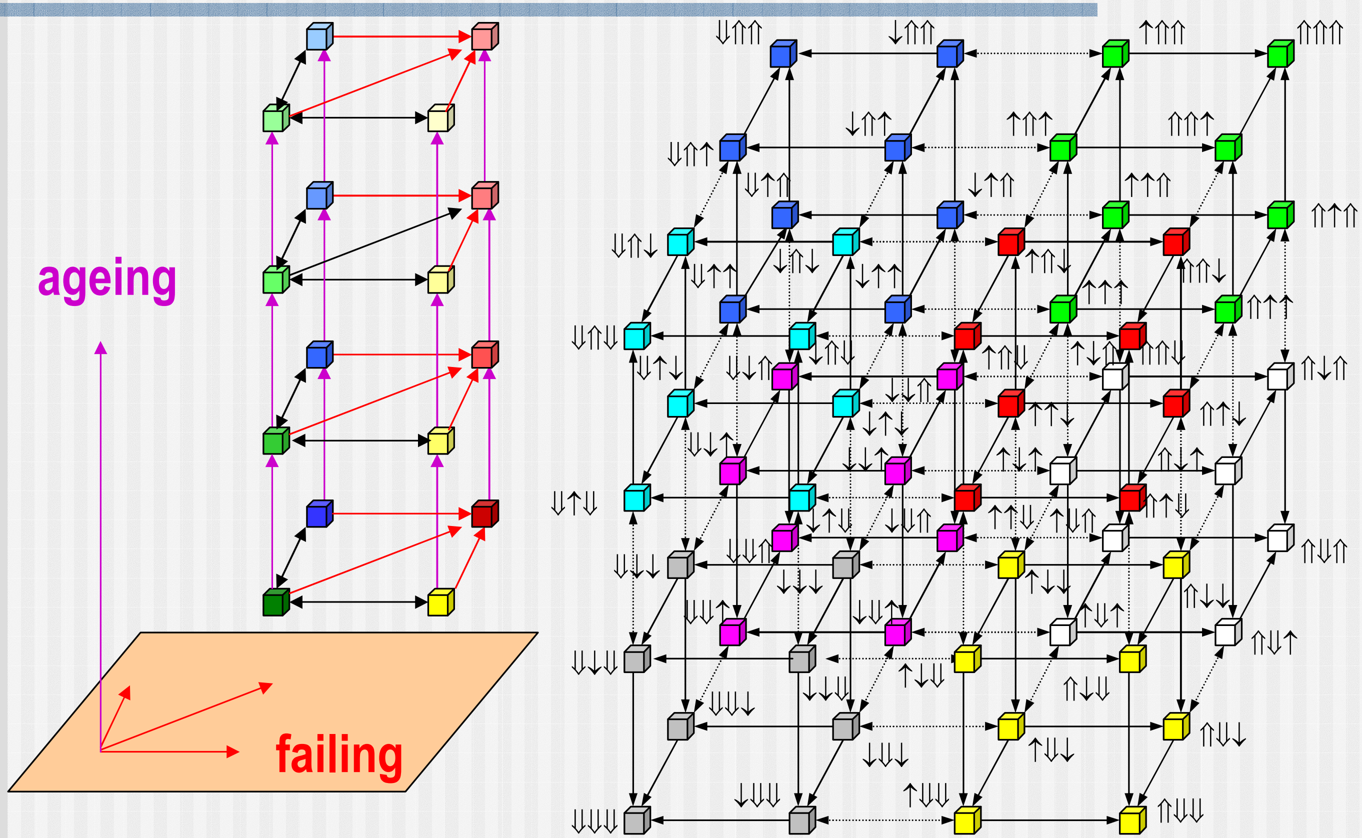
ATRD Methodology

- The ATRD method uses inductive logic, where every physical and logical connection should be expressed in an explicit form.
- The ATRD system model is a digraph of system functioning. Reliability networks are presented as stochastically independent or dependent graphs.
- The multiple network with control links (Petri Nets elements) or places can discretely, hierarchically and dynamically change the state of the system components.

Aging ATRD 'Cell-to-Cell' Procedure



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Age-dependent models for incorporating into unrepairable component reliability

- The **linear ageing failure rate models** for *unrepairable* equipment:

$$\lambda(w) = \lambda_0 + \alpha w \qquad (1)$$

where $\boldsymbol{w=(t-\tau)}$ is the **age**, $\boldsymbol{t}$ is the global time, λ_0 is the pre-ageing failure rate of a new component) τ is the threshold time at which ageing starts, α is the rate of ageing and $\lambda(t)$ is the total failure rate.

- Some of the results for the ageing failure probability do not agree with linear ageing model, e.g. flow accelerated corrosion.
- In such cases the **two-parameter Weibull ageing failure rate model** is chosen:

$$\lambda(w) = \lambda_0 + \alpha(\beta + 1)w^{\beta} \qquad (2)$$

where α is a scale parameter, β is a shape parameter and τ is a location parameter

Age-dependent models for incorporating into repairable component availability

- The linear and Weibull ageing models could be easily used for *repairable* components by insertion ***t'*** as a local time at which last repair/restoration was completed. The failure intensities are given by:

$$\lambda(w) = \lambda_0 + \alpha(w - t') \quad (3)$$

$$\lambda(w) = \lambda_0 + \alpha(\beta + 1)(w - t')^{\beta} \quad (4)$$

- The second simple way to take into account incompleteness of restoration or repair is based on the use of degradation factor ***γ(w)*** (**0<γ<1**) or equivalent **one-parameter Weibull ageing failure rate model**:

$$\lambda(w) = \lambda_0 / \gamma^{i-1} \quad (5)$$

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Applicability of dynamic system and process reliability methods

- Confirmation the ET-FT ageing-screening analysis
- Information about ageing effects of local models on the PRA model.
- Corroboration or rejection of the hypotheses embedded into hybrid deterministic-probabilistic models
- Gaining a deep physical understanding of the models
- Controlling the output uncertainty and identifying the dominant parameters
- Ageing PRA model quality control - sensitivity studies

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Objective and Scope of the Incorporating of Ageing Effects Case Studies

- The main objective of the case studies is to demonstrate the process of incorporating ageing effects for NPP active and passive components into different system reliability models by implicit and explicit reliability methods and benchmarking their results with FT method.
- The scope covers the following:
  - Implementation of the ageing effects into safety and normal operation systems reliability models by different methods - FT, GO-FLOW and ATRD) for typical mechanical components: valves, pumps, heat exchangers, tanks, filters and pipes.
  - Determination of the ageing impact on component unavailability.
  - Assessment of the maintenance sensitivity to the ageing effects.

Case Studies for Incorporating of Ageing Effects into System Reliability Models

- The two case studies investigate the feasibility of dynamic system reliability methods (GO-FLOW and ATRD) to model the unavailability of ageing components of safety and normal operation systems of a Russian-design PWR WWER-1000/V320:
  - Safety system - the 3-train LP RHR/ECCS –TQ_2
  - Normal operation system - the OS of MCP – YD50, 60
- The possible extensions of three methods are compared with the equivalent RHR/ECCS & OS FT models in which static component unavailability calculated forms are used.

Current FT, ATRD and GO-FLOW Reliability Models Features

- In the GO-FLOW model 4 types of operators are used:
  1. Type 25 – signal generator;
  2. Type 26 an 27 – normally open and closed contacts;
  3. Type 35 – failure during operation.
- The current ATRD & GO-FLOW models are intended just to repeat assumptions & results of the FT models.
- The FTs were converted into the GO-FLOW and ATRD software using the same settings and equivalent reliability models as in SAPHIRE.
- The validation acceptance has been considered based on the similarity of results - similar probabilities of BEs.

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Case Studies Implementation and Comprising Ageing Components

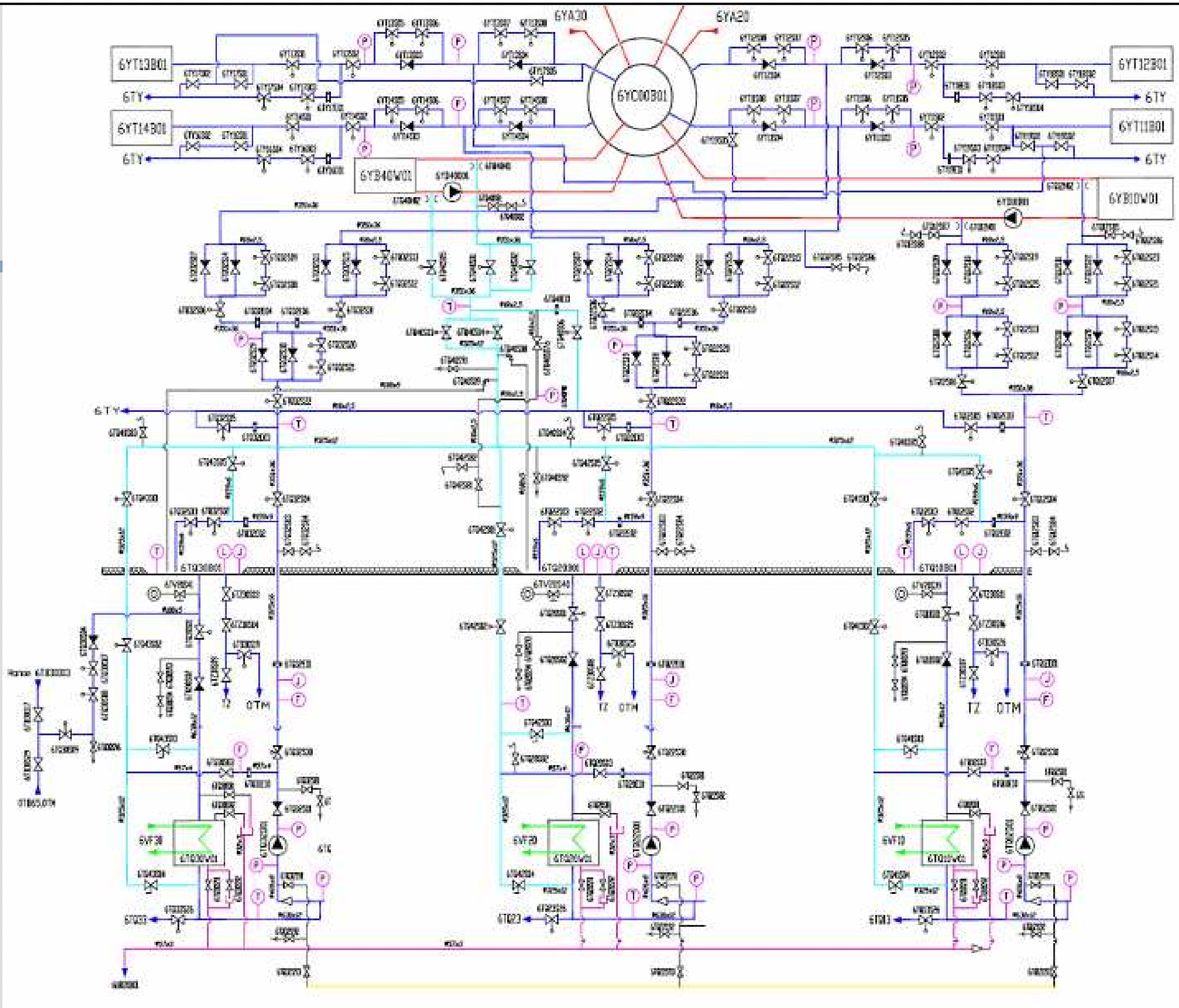
- The case studies are implemented in three steps:
  1. Identify the components to be assessed.
  2. Analyse the ageing time-dependent effects and calculate their failure and repair rates.
  3. Ageing effects sensitivity analysis
- The case studies comprise 3 categories of ageing components:
  - *restorable replaceable* – valves, pneumatic valves, pumps, filters;
  - *non-restorable replaceable* – check valves and pipes;
  - *restorable hard-to-replace* – tanks and heat exchangers.

Description of the RHRS of WWER-1000

- The RHRS has to perform two functions/regimes:

1. low pressure injection in case of LB LOCA – *regime 'I'*;
2. emergency and planned core cooling – *regime 'P'*.

- The RHRS consists of three trains with electrically driven pump, 3x100%, supplied from normal and emergency power supply systems; a heat exchanger, valves, check valves and a common tank for all three channels.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6YB10W01
6TY
6TQ30B01
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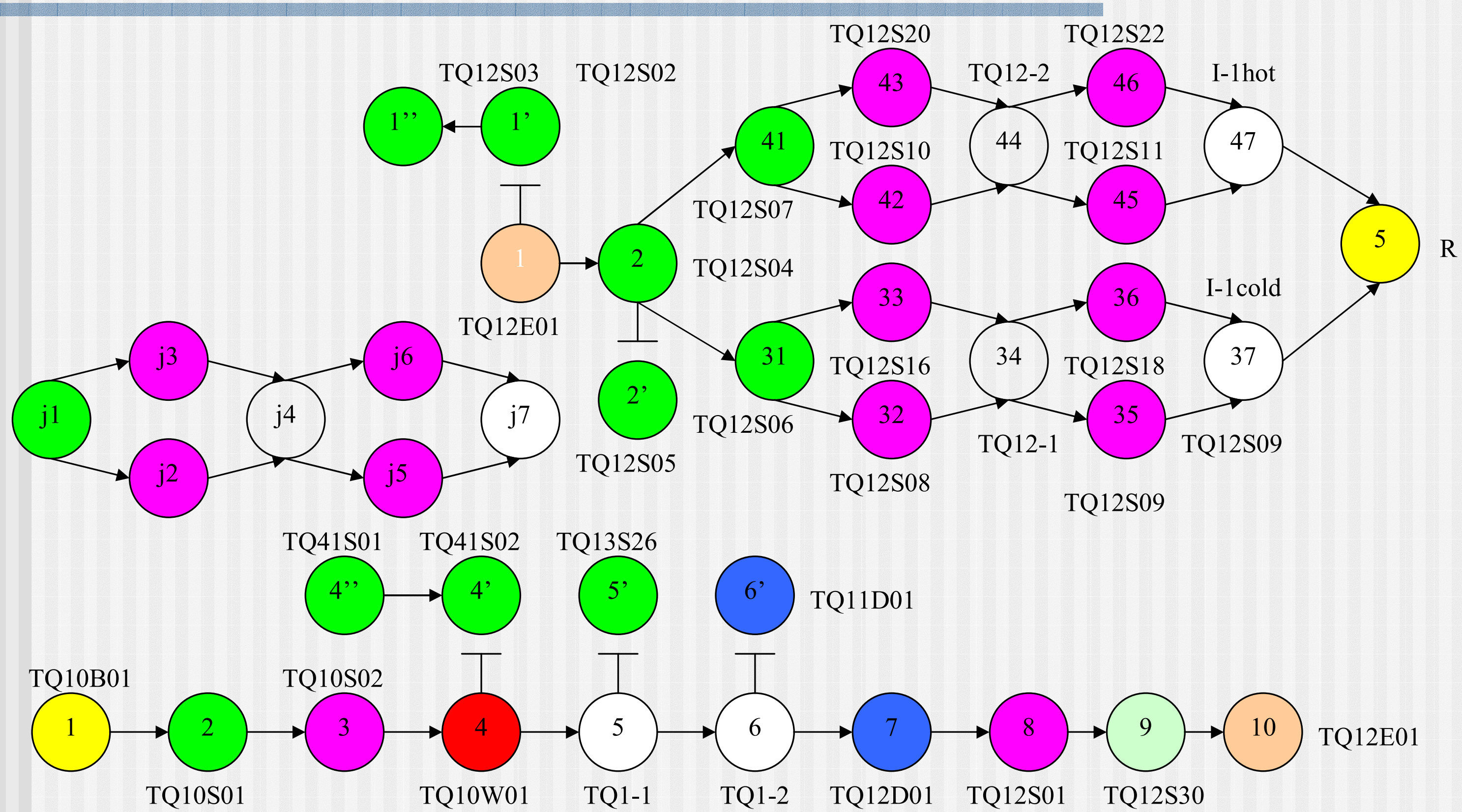
The ATRD Model of Injection by the TQ12 Train



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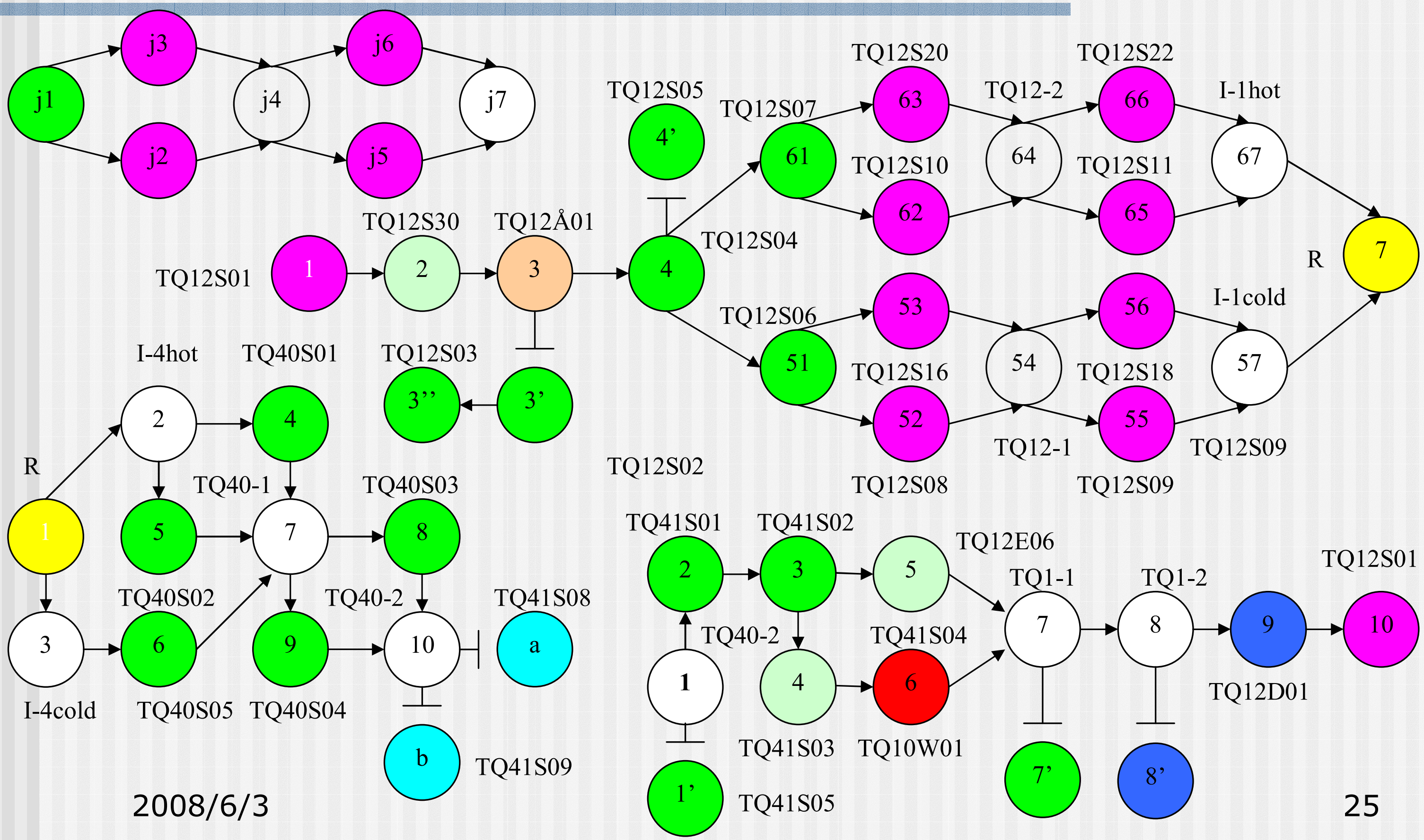
The ATRD Model of Cooling by the TQ12 Train



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Selection of Basic Events for Ageing Analysis for the WWER-1000 ECC/RHRS

- The selection criterion of BEs for ageing analysis relies on the unavailabilities and Fussel-Vesely importance measures.

N	BE	Failure Mode	Probability	FV Injection	FV Cooling	λ , y $^{-1}$ /d^{-1}	T, d
1	P_S	Fails to Start	1.56E-03	3.078E-03	-	1.90E-02	30
2	P_R	Fails Running	3.60E-04	6.362E-04	-	1.30E-01	1
3	EV_O	Fails to Open	3.17E-02	2,491E-02	-	4.03E-02	300
4	RV_DC	Fails to Stay Closed	7.20E-05	-	3,977E-03	2.63E-02	1
5	CV_O	Fails to Stay Opened	1.01E-04	-	1,730E-04	1.23E-03	30
6	W_Y	Leakage	1.22E-04	2.094E-04	-	1.48E-03	30
7	EV_O_CCF	CCF Fails to Open	3.21E-03	4,696E-02	6,692E-02	4.03E-03	300
8	P_S_CCF	CCF Fails to Start	7,80E-05	3,024E-03	4,309E-03	9,49E-04	30

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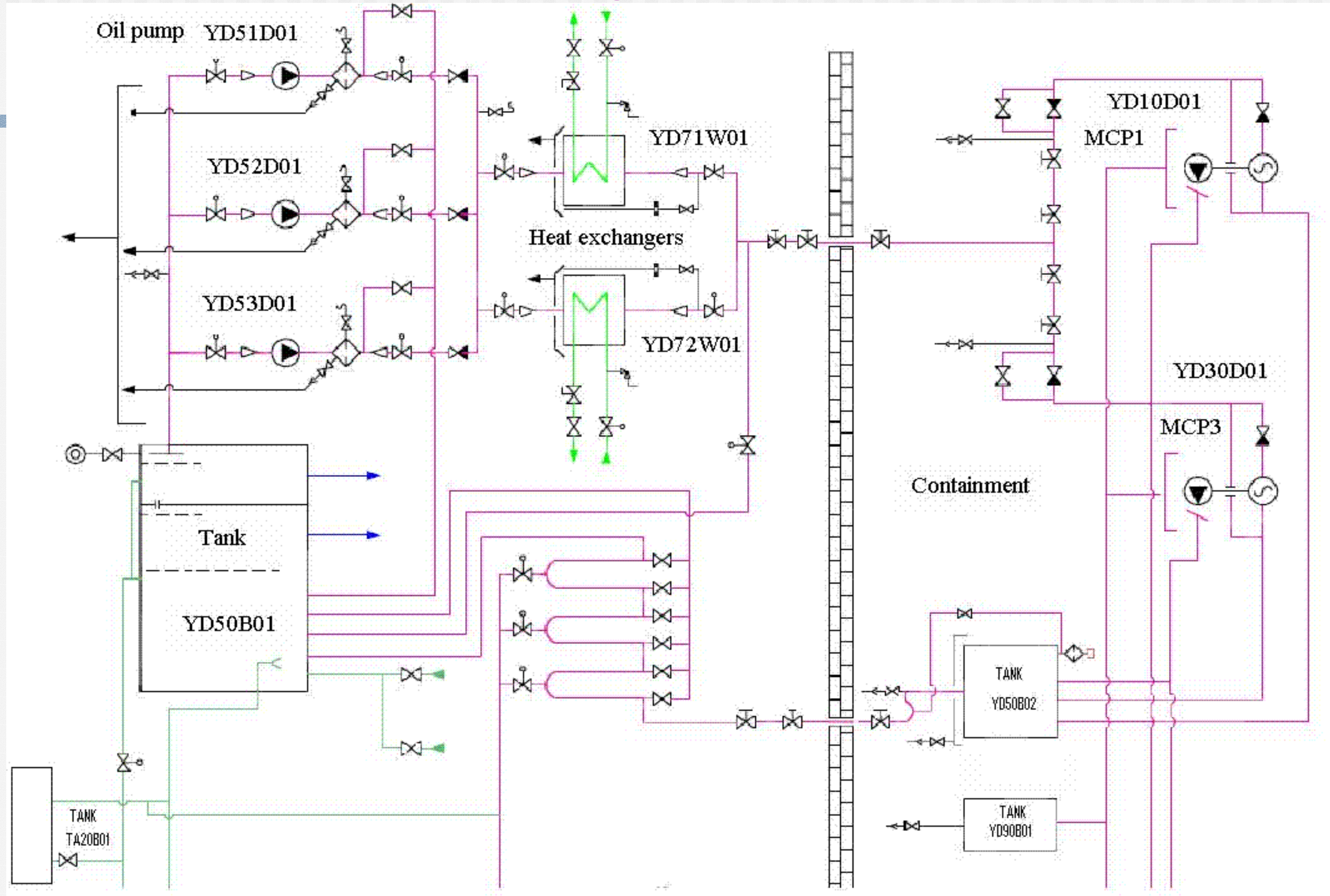
Description of the Oil System of Main Coolant Pumps of WWER-1000

- The OS of MCP has to perform the functions of lubrication and cooling of the MCP bearings.
- The OS is presented by 2 functional groups YD50 and YD60 (each of them supplies two MCPs) – *regime 1*.
- If one MCP is not working then the recirculation of OS is open – *regime* 2.
- Each functional group consists of three electrically driven pumps with pump oil filters, 3x100%, supplied by normal power supply system; 2 heat exchangers, valves, check valves, normal and emergency pneumatic valves, hydraulic lock, 2 normal and 2 emergency operation common tanks.

WWER-1000 Oil System of MCP1&MCP3



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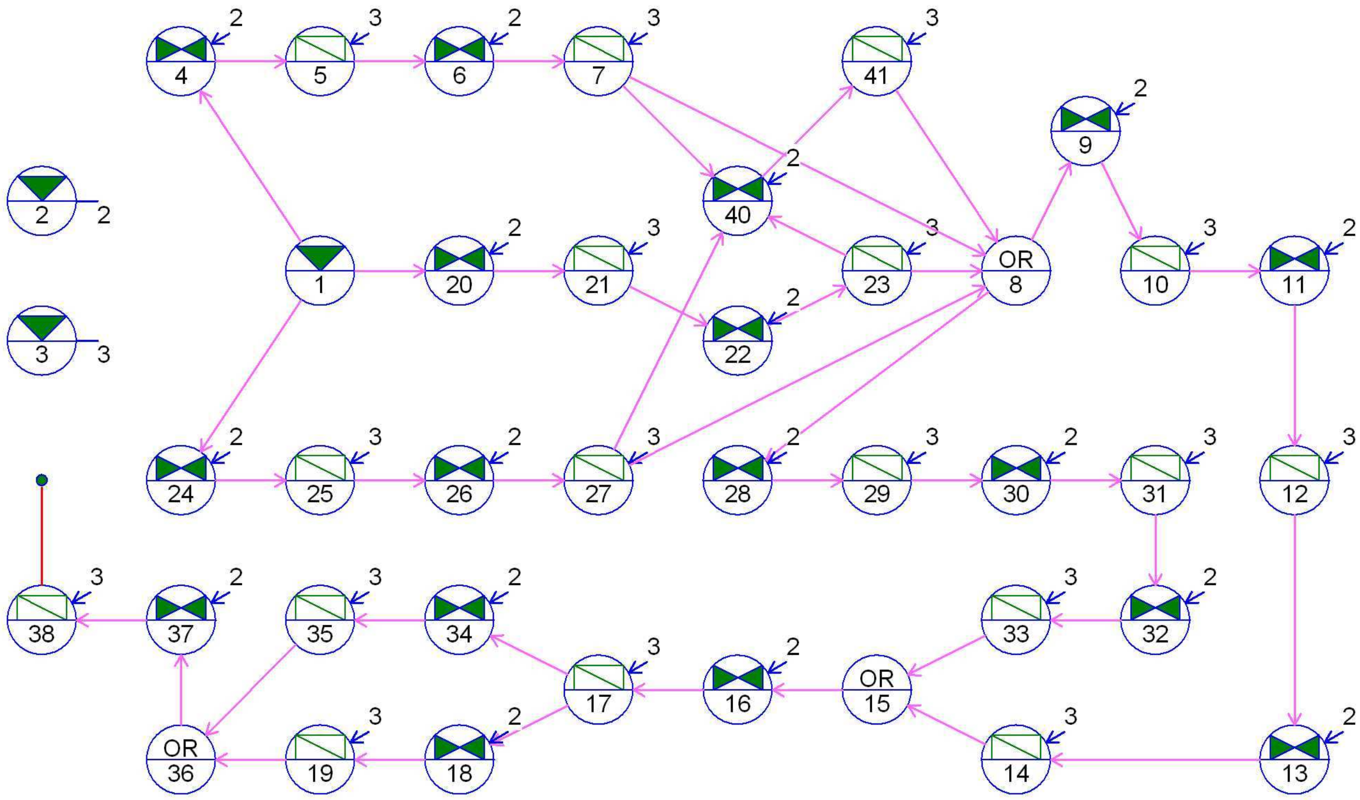
The GO-FLOW Model of the Oil System YD50 Train



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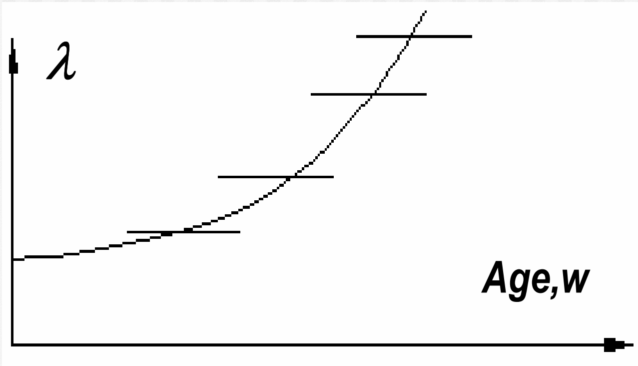
Selection of Basic Events for Ageing Analysis for the WWER-1000 OS of MCP

- The selection criterion of BEs for ageing analysis relies on the unavailabilities, Fussel-Vesely importance measures and number of components.

N	BE	Failure Mode	Probability	FV1	FV2	Numbers	λ, h^{-1}	T, d
1	P_S_CCF	CCF Fails to Start	0,0005	1,8E-3	-	6	1E-6	30
2	P_R_CCF	CCF Fails Running	0,0009	1,1E-3	-	6	1E-5	1
3	PV_DO	Fails to Stay Open	0,14	-	1,4E-2	12	2E-4	300
4	PV_C	Fails to Close	0,007	-	7E-4	8	2E-6	300
5	W_Y	Leakage	0,0001	2,4E-4	-	4	3E-8	15

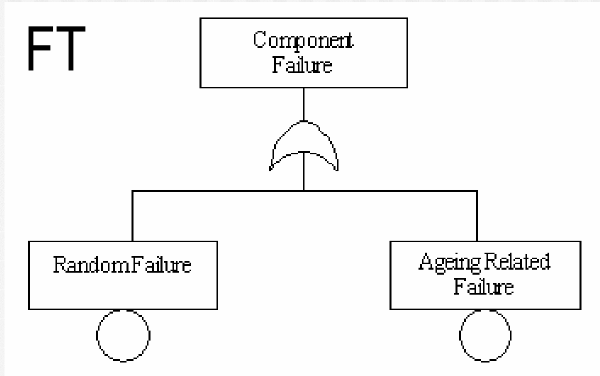
Incorporation of Ageing Effects into FT, ATRD and GO-FLOW Models

- Stepwise Weibull Approach

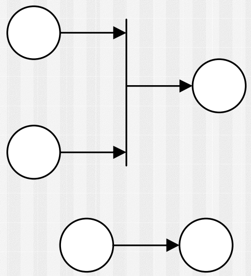


- Ageing failure rates with Weibull distribution as subjective estimates on the base of engineering judgment and generic data (TRIGALEX) for linear ageing rates of selected components

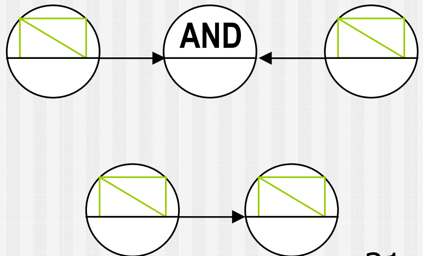
- BE Decomposition Approach



ATRD



GO-FLOW



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Ageing effects sensitivity analysis

- The linear ageing models for *unrepairable* (check valve) and *repairable* (pump) equipment are used:
- **check valve**: λ_0^{CV}=1,75.10^{-3} y^{-1}, a^{CV} =2,63.10^{-8} y^{-2}, τ_{CV}=0,

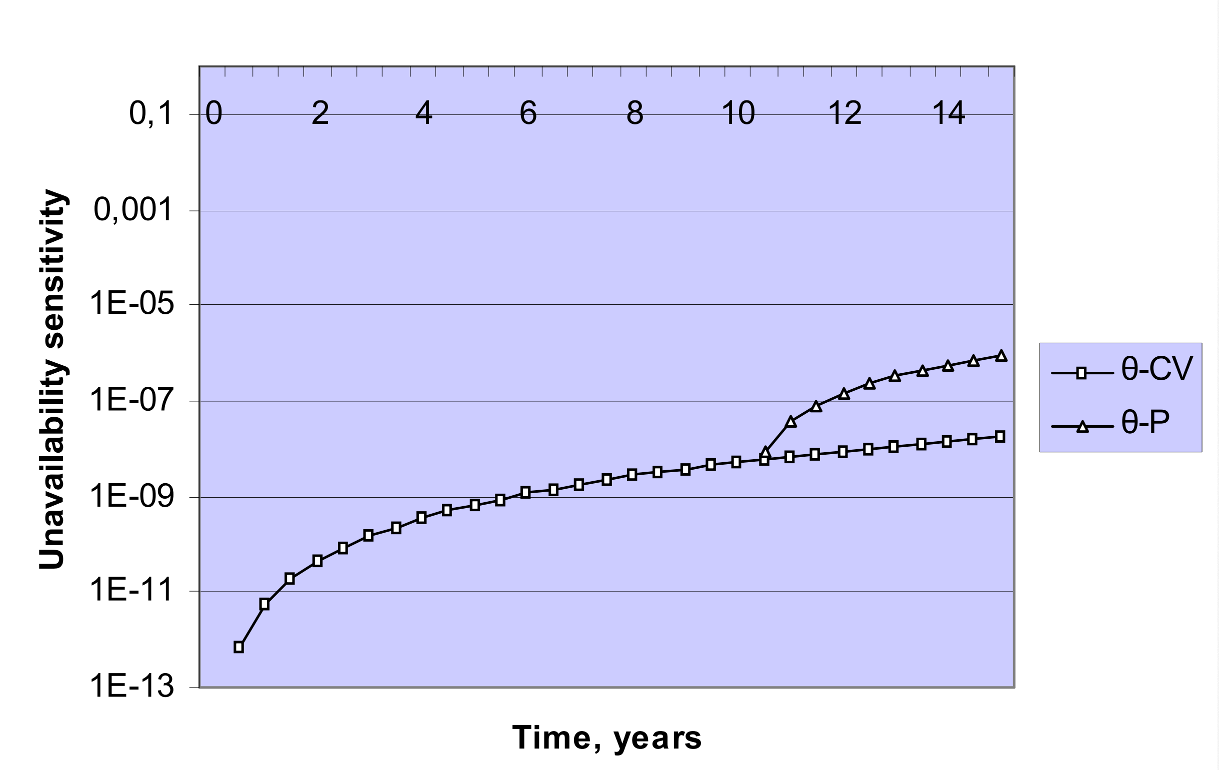
$$\lambda^{CV}(t-\tau)=\lambda_0^{CV}+a^{CV}(t-\tau_{CV}) \qquad \theta_{\_CV} \approx \frac{dQ_{RHRS\#2}}{dq_{CV}}[\lambda^{CV}(t)-\lambda_0^{CV}]$$

- **pump**: λ_0^P=8,76.10^{-1} y^{-1}, a_λ^P =7,88.10^{-6} y^{-2}, μ_0^P=12 y^{-1}, a_μ^P =7,88.10^{-5} y^{-2}, τ_P=10, where

$$\lambda^P(w)=\lambda_0^P+a_\lambda^P(w-t') \qquad \theta_{\_P}=\theta_{\_P\_l}=\frac{dQ_{RHRS\#2}}{dq_P}[\lambda^P(w)-\lambda_0^P]$$

$$\mu^P(w)=\mu_0^P+a_\mu^P(w-t') \qquad \theta_{\_P\_m}=-\frac{dQ_{RHRS\#2}}{dq_P}[\mu^P(w)-\mu_0^P]$$

Unavailability sensitivity comparison of a non-repairable check valve and a repairable pump



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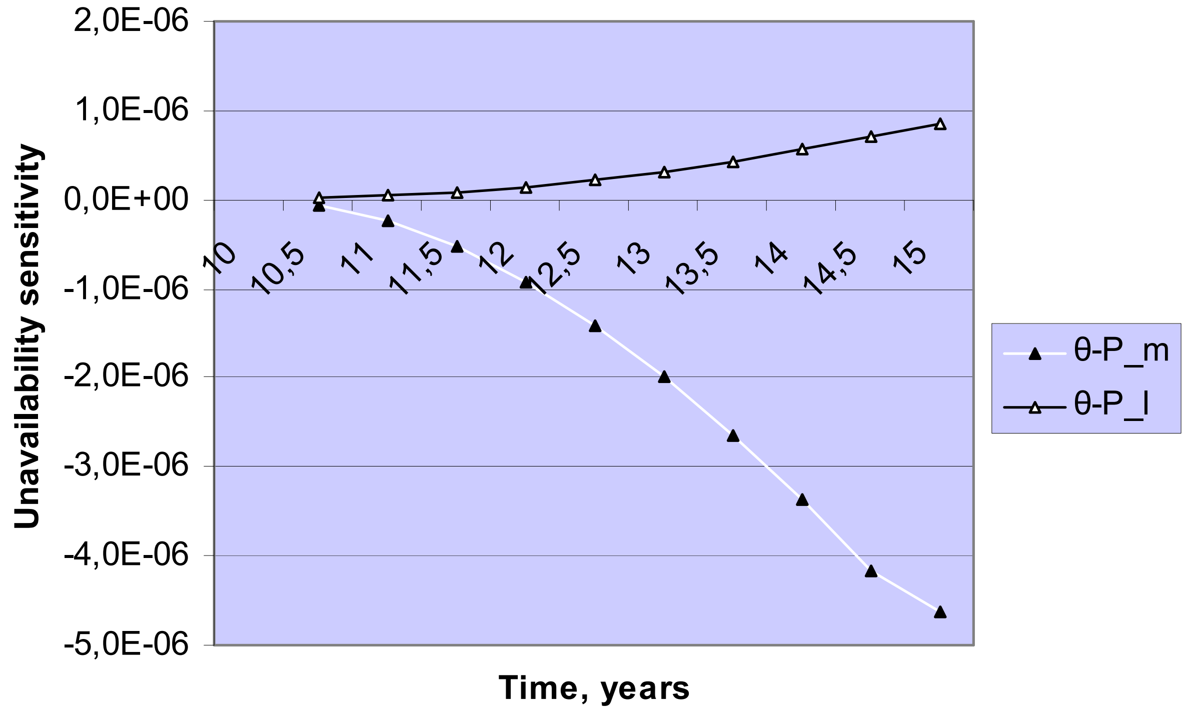
Ageing unavailability sensitivity comparison of ageing & non-ageing repairable pump with changed surveillance interval



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Insights 1

- The dynamic system reliability methods could be used to allocate the ageing reliability data for basic events and ageing failure mode and effect analysis.
- The ageing processes description of safety systems differs from the processes of normal operation systems and must include ageing in working and stand-by states at different intervals.
- The failure mode database is concerned with component functions and rarely with physical component processes, including ageing related processes.
- It means that only a part of component failure modes should be suspected of ageing.
- The quantification of age-related degradation effects must be sensitive to component's function.
- The GO-FLOW and ATRD methods could be used for calculation and synchronization of the ageing impact to the safety system and normal operation system component unavailabilities .
- They may extrapolate and predict the component unavailability curves up to stationary values in different time intervals and to the end of the plant lifetime.

Insights 2

- ATRD seems more appropriate for explicit obtaining of dynamic component unavailability functions and data preparation because the GO-FLOW results depend on calculation step and available operator type values. However, the GO-FLOW operators could be extended and adapted to ageing processes.
- GO-FLOW could be especially useful for extrapolation of component/system unavailability curves in different time intervals.
- All dynamic system reliability methods could be used to propose the optimal periodical test and preventive maintenance intervals for components based on determined options and criteria.
- A practicable approach seems to be the use of different individual ageing process with component degradation and restoration factors.
- The shortening of surveillance intervals for renewable components, as an ageing compensation measure, would be more explicitly modeled and treated in PSA if a restoration factor, similar to degradation factor, is introduced.

Conclusions

- The equivalent FT, GO-FLOW and ATRD models/data have been compared and validated based on identity of results. The process of incorporating ageing effects into three different models has been demonstrated by using two approaches:
  - stepwise Weibull approximation
  - basic event decomposition.
- The FT, GO-FLOW and ATRD models were applied for several typical components in order to evaluate the ageing impact.
  - The increase of failure rate increases unavailability of safety system components – the WWER-1000 ECC/RHRS models;
  - The increase in component failure rate of normal operation system - Oil System of MCPs - could cause an increase in the system upset frequency, including the frequency of accident initiators.

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Thank you for your attention!

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